AN UPDATE ON THE PERFORMANCE OF THE *IN SITU* ^{14}C EXTRACTION LINE AT THE UNIVERSITY OF BERN

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Keywords: meteorites, radiocarbon dating, terrestrial age

ABSTRACT

We present the current performance of the *in situ* ^{14}C extraction line at the University of Bern with an improved extraction and combustion system. After three major steps of improvement, the extraction of sample CO_2 gas now takes place inside a platinum crucible, supported by an outer quartz-glass crucible. This set-up allows us to operate the line as a closed system for several samples without breaking the vacuum. Measurements of procedural blanks and samples from our reference strewn field, Jiddat al Harasis 073, performed in our system all show a good reproducibility and, for the strewn field samples, consistency with published data. We describe each improvement step in detail, describing the advantages and disadvantages of all tested set-ups. By sharing our knowledge, we aim to inform and prevent others from making the same or similar detours in establishing ^{14}C extraction systems for extraterrestrial samples.

1. INTRODUCTION

The performance of the ^{14}C extraction line located at the Physics Institute at the University of Bern has been first described by Mészáros et al. (2018). While the performance of the first set-up of the system was already satisfactory, further improvements were necessary. Therefore, since the first publication, the system has undergone three significant changes and improvements concerning the gas extraction unit, especially considering the type of the heating apparatus and the material and set-up of the crucible. Here, we present a summary of data for each improvement step and we list the advantages and disadvantages of each set-up. Our aim is to inform the reader about the chain of technical developments to prevent making the same or similar detours for future projects in establishing ^{14}C extraction systems for extraterrestrial samples. In addition, we discuss the analytical reproducibility and the accuracy of the current system and we describe our revised extraction protocol.

The major difference between ours and other ^{14}C extraction systems is that we aim for a 'closed system', i.e., we want to be able to measure several samples in a row, without breaking the vacuum. This makes our system more time efficient and allows for a higher sample throughput. Currently, the system's gas extraction unit is composed of a custom-made platinum (Pt) crucible coupled to a radio frequency generator (RF), allowing us to measure several samples before breaking the vacuum. Note, that high ^{14}C concentrations in extraterrestrial samples allow for a closed system, whilst still measuring small sample aliquots. The same does not apply to systems designated for terrestrial samples where the ^{14}C concentrations are significantly lower, hence larger sample aliquots must be used.

Amongst its well-known applications in archeology and Earth sciences, radiocarbon dating is routinely used for terrestrial age determination of stony meteorites, in particular those found in hot deserts (e.g., Jull 2001, 2006). This method is based on the radioactive decay of cosmogenic *in situ* ^{14}C, produced by spallation reactions induced by primary and secondary galactic cosmic ray (GCR) particles (Reedy and Arnold 1972). The major target element for cosmogenic ^{14}C production in stony meteorite and planetary surfaces is O, though spallation reactions on Mg, Al, Si, Ca, Fe, and Ni also produce *in situ* ^{14}C. Their contributions, however, are significantly smaller (Born and Begemann 1975; Leya et al. 2001). Apart from the production in space, cosmogenic *in situ* ^{14}C is also produced on the Earth surface, but in amounts approximately 220 to 1600 times smaller than in space (e.g., Lifton et al. 2001, Jull et al. 2013). Therefore, contributions from terrestrial production of *in situ* ^{14}C are usually considered negligible.

Samples of Interest

We focus on the study of chondritic meteorite strewn fields from hot deserts. The samples of interest were collected in the Sultanate of Oman (see Motivation section) and are readily available in the collection at the Natural History Museum in Bern. Chondrites account for ~80% of all observed meteorite falls and of ~90% of all recovered meteorites (Meteoritical Bulletin Database, as of 10 Oct 2019; also see, e.g., Grady 2000), hence sufficient material is available for study and comparison. Major minerals in which ^{14}C is produced in ordinary chondrites are olivine ($(Mg,Fe)_2SiO_4$) and pyroxene ($(Mg,Fe)SiO_3$). In a rock mixture, the melting point of olivine is ~1200°C and for pyroxene it is slightly below 1200°C. Consequently, our extraction system must be able to heat samples to >1200°C to ensure melting of the major minerals and extraction of *in situ* ^{14}C.

The reference we have chosen as a test for the performance of our extraction system is the well-documented L6 chondrite Jiddat al Harasis (JaH) 073 strewn field found in the Sultanate of Oman in 2002. The strewn field covers an area of 114 km^2 and consists of 3463 single stones with a total mass of 600.8 kg, as of 2009 (Gnos et al. 2009). The previously measured mean ^{14}C age of JaH 073 is 19.7 ka (Al-Kathiri et al. 2005) and the mean $^{14}C/^{10}Be$ age is 14.4 ka (Gnos et al. 2009).

2. METHODS

a. Motivation

Our major motivation to establish a ^{14}C extraction system was to be able to study the terrestrial ages for the large number of meteorites collected over the years in the Omani-Swiss search campaigns (Hofmann et al. 2011, 2014). As described by Mészáros et al. (2018), our combustion- and extraction-system is loosely related to the former ^{14}C extraction line developed at ETH Zürich (Hippe et al. 2009, 2013), which was recently replaced by a new design extraction line described in Lupker et al. 2019. The former system at ETH used an electron bombardment furnace with a two-vacuum system, in which a tungsten tube hosted a sapphire tube, separating the outer from the inner vacuum. Samples, typically 5 g of purified quartz, were placed into a small Pt-crucible, which hanged inside the sapphire tube. After sample degassing, the inner vacuum would be broken, and the small Pt-crucible would be removed and cleaned for the next sample. While the blank of the system was impressively low, the sample throughput was moderate at best, with preparation and cleaning taking a few days for each sample. Please, note that for our purpose we define ‘combustion’ as melting and oxidation, hence we refer to our system as a combustion-extraction system.

A system that claims fast and reliable sample throughput has recently been installed at the University of Cologne, Germany (Fülöp et al. 2015). The extraction procedure consists of, *first*, an in-vacuo heating step at 10^{-8} mbar and 500°C for 2 hours. After this cleaning step samples, which are in fused-silica tubes, are sealed and weighted for the next step, the combustion. Here, the tube-sealed samples are placed in an air-resistance tube furnace and are heated to 1650°C under a continuous N_2 flow for 2 hours. Subsequently, samples are again sealed and this time they are transferred to an all-metal UHV extraction system for cleaning. The advantage of this modular system is that samples are processed in batches of three to five. The major difference to most of the other ^{14}C extraction systems is that sample degassing and gas cleaning steps are separated. Note that the recently presented ^{14}C extraction line at the University of Wollongong, Australia, is a copy of the extraction line in Cologne, except that the number of samples per batch can vary between three and six (Fülöp et al. 2019).

The system recently installed at the ^{14}C laboratory at the Purdue Rare Isotope Measurement Laboratory (PRIME Lab) has been automated with the goal to speed up gas extraction and cleaning (Lifton et al. 2001, 2015). This system originally started with an Al_2O_3 crucible that failed structurally. This has been changed to a mullite-type crucible (60% Al_2O_3 and 40% SiO_2). Mullite softens at 1300°C – 1325°C, i.e., much too low to be useful for melting quartz. Therefore, the system now uses $LiBO_2$ (Lithium metaborate) as a flux agent to reduce the melting point for quartz to temperatures low enough that can be handled with the used extraction unit. However, a full analysis of a sample still requires more than one day and after each sample the vacuum must be broken (e.g. Lifton et al. 2001, 2015).

b. Modifications

i. In-air Convection Oven combined with an Al_2O_3 Crucible: November 2016 till February 2017

The first modification of the gas extraction system is already described by Mészáros et al. (2018). In its original version, the extraction setup consisted of an in-air convection oven, i.e., while the inside of the crucible was under vacuum, the outside of the crucible was in air. Such a setup requires that the crucible can be heated in air up to 1800°C without being damaged, and equally important, that the crucible remains vacuum-tight. These requirements significantly limited our options for the crucible material. We considered aluminum oxide (Al_2O_3) a promising material and we manufactured Al_2O_3-crucibles, in which samples were combusted in O_2 partial pressures of 30(±5) mbar (for a detailed description of the setup and the extraction procedure see Mészáros et al. 2018). During gas recovery experiments in which a known amount of CO_2 gas was processed like a sample, i.e., the gas was introduced into the extraction system connected to the hot crucible, frozen into the cold finger charcoals, and was finally collected into a capillary, CO_2 losses of up to 14% were detected. An inspection of the crucible showed no visible damage or cracks and there was also no measurable increase in porosity. Therefore, the CO_2 loss remained unexplained; yet we speculate that the remainder of the material studied before (multiple pieces of aluminum foil together with meteorite aliquots) have become porous after several heating cycles and eventually began to partially take up CO_2 gas. Note that Lifton (1997) and Lifton et al. (2001) also found that their Al_2O_3 furnace tube failed structurally. While the remaining blanks were very low the CO_2 recovery was also low and the authors concluded that the alumina surface somehow got activated and started absorbing CO_2. Note that the chemical reactions taking place inside a hot Al_2O_3-crucible and in an O_2 partial pressure are complex and not well-understood.

Owing to the unexpected and poor behavior of the Al_2O_3-crucible, we changed the set-up to an iridium (Ir) crucible. Though the Al_2O_3-crucible setup did not work as expected, its advantages would have been manifold. The extraction unit was relatively cheap, easily installed, and easily mended. The most

expensive part was welding the Al_2O_3-crucible into the water-cooled metal flange. The major disadvantage (besides the structural failure) was a long heating cycle. For example, heating the crucible from room temperature up to 1600°C took ~160 min (10°C min^{-1} temperature increase) and cooling the crucible down to ~340°C took another ~180 min. The relatively long heating cycle was necessary to avoid cracking the crucible due to its low thermal conductivity. Note that longer heating cycles often produces higher blanks.

ii. Convection Oven and Ir-Crucible: February 2017 till January 2018

The Ir-crucible replaced the Al_2O_3-crucible in February 2017. The meteorite data published by Mészáros et. al. (2018) were all obtained using the Ir-crucible. The main advantages of this extraction unit were easy maintenance and a relatively quick heating cycle, with 50°C min^{-1} temperature change. The shorter heating cycles resulted in quicker extractions, usually producing lower blanks. The major disadvantage of this system was the high cost of the (custom-made) Ir-crucible. Though Mészáros et al. (2018) managed to complete their measurements using this setup, as more samples were studied, the Ir-crucible started to degas. After thorough testing, we were able to demonstrate that the degassing had no effect on the measurements, i.e., the released gas was free of CO_2. However, the system had to be continuously pumped to avoid pump damage and/or failure of other vacuum components. For example, introducing 25-27 mbar of CO_2 gas into the cold crucible and disconnecting the extraction line from the pump resulted in a pressure increase of more than a factor of 50, i.e., from lower than 5.0×10^{-4} mbar to 0.1 mbar, in just 20 min. Though, this pressure is still much smaller than the 25-30 mbar O_2 partial pressure used for the combustion, we nevertheless decided to again change the set-up to have more confidence in the extraction unit and in the final data. After identifying the problem, the Ir-crucible was removed, emptied, and carefully examined, and no inherent damage was found. Therefore, currently the degassing cannot be explained but nevertheless it prohibited further use of the Ir-crucible. Note that Lifton et al. (2001) also argued that metals can react with the carbon released from the sample, thus affecting the carbon yields.

iii. High Frequency Generator, Double-walled Quartz Glass Crucible, and Combustion Catalyst: January 2018 till November 2018

1. Iron Pellets as a Combustion Catalyst

In all earlier set-ups, the crucibles proved to be the most problematic part of the system. The role of a crucible is to provide a vacuum barrier, thereby be resistant against oxidation and/or other types of alteration, while being heated in air (outside the crucible) or under oxygen partial pressure (inside the crucible). Finding suitable crucible materials proved to be challenging. Therefore, we decided to significantly change our combustion and extraction set-up to one where the crucible is no longer directly heated. A system made of two quartz (Qtz) glass crucibles combined with RF heating was such a set-up. The following changes were made: A High Frequency Generator (HFG) HTG-10.00/0.45 N (Linn High Therm®) replaced the formerly used convection oven, and the single crucible setup (either Al_2O_3 or Ir) was changed to a double-walled Qtz-crucible system. An outer Qtz-crucible, with a length of 350 mm, outer diameter of 20 mm, and wall thickness of 2 mm, served as a vacuum barrier. Inside the outer crucible, we placed an inner Qtz-crucible with the length of 330 mm, an outer diameter of 13 mm, and wall thickness of 1 mm. The bottom 2 cm of the outer crucible was filled with Qtz-granulate to prevent a direct heat contact between the inner and the outer crucible. Also, the bottom 1 cm of the inner crucible was filled with Qtz-granulate to prevent a direct contact of a heated sample with the crucible wall. The

outer Qtz-glass crucible provided the vacuum barrier and was only heated by the energy radiated by the hot sample. However, RF induction heating only works for materials which are good electric conductors. While this may apply to freshly fallen and relatively iron-rich meteorites, it does not hold for old, highly weathered meteorites in which most of the metal has been oxidized. Most of the samples currently studied by us are ordinary chondrites (see Samples of Interest), most with significant signs of weathering. Consequently, they cannot be heated using RF. This shortcoming in combination with the desire to build an extraction system as versatile as possible, we decided to add two pellets of high purity iron (Fe; 99.99+%; 180 mg/piece) to each sample to act as the heating source. In our system, samples are introduced via a manual manipulator into the crucible from a sample storage holder located above the crucible. Therefore, the landing position of each sample inside the inner crucible is random and the hot sample might be in contact to the glass wall and potentially break it. The outer crucible in contrast is never in direct contact to the hot sample, which is a much safer set-up. Even if the inner crucible breaks there is still the outer crucible acting as the vacuum barrier.

This set-up had several advantages: It was easy and cheap to install and relatively inexpensive to run. In addition, a double-crucible set-up is inherently safe. For example, after some measurements the inner crucible eventually cracked at the position where one of the samples got molten. However, even after the inner crucible had cracked, the system remained fully operational. As a precaution we decided to nevertheless replace the inner crucible in case it would no longer hold back the molten material, which in turn could pose a threat of damaging the outer crucible and breaking the vacuum. However, there were some major drawbacks for this set-up. *First*, the walls of the inner crucible had to be cleaned with hydrochloric acid (HCl) to remove the significant iron oxide condensation. This cleaning was necessary at least after every second sample, i.e., after 8 measurements, and it took 1-2 days depending on the thickness of the iron oxide deposits. This significantly reduced the sample throughput. *Second*, the extraction set-up worked only for two meteorite samples, i.e., 8 measurements, before the blanks increased to levels at which the number of extracted ^{14}C atoms was similar to that for typical meteorite extractions.

Table 1 summarizes all measurements completed using this set-up. In total, four aliquots of the JaH 073 strewn field, our reference sample, were measured - three with applying a pre-heating procedure and one without pre-heating. The blank values given in Table 1 are distinguished into system blanks (BL_2FE) and procedural blanks (NI) (see also Mészáros et al. 2018). The first measurements of the JaH 073 aliquots were in good agreement with literature data (Gnos et al. 2009, Mészáros et al. 2018). Further measurements, however, suffered from a gradual increase in the number of extracted ^{14}C atoms and it was never entirely clear whether the extra ^{14}C atoms came from the previous, not completely combusted samples, from the Fe-pellets, or from both. Though the number of ^{14}C atoms per gram sample was more or less consistent for all measured aliquots, the sample re-extractions showed a gradual increase in the number of extracted ^{14}C atoms, clearly indicating that the previous samples were not completely extracted. For example, the re-extraction of a JaH 073 aliquot measured in August 2018 gave 86.2 (±0.9)×10^4 ^{14}C atoms, whereas the main extraction of the sample itself gave 113 (±2)×10^4 ^{14}C atoms, i.e., only slightly more. Therefore, with this set-up was impossible to prove complete ^{14}C extraction from samples and to guarantee that there was no cross contamination among the different samples.

There were two major difficulties that prevented routine application of the described extraction system. *First*, once the Fe-pellets reached their melting temperature of ~1540°C, as indicated by the bright yellow to white glow and the changes in the shape of the pellets, they oxidized extremely fast, thereby losing their electric conductivity. Since RF heating is only applicable to electric conductors, the oxidized Fe pellets could no longer be heated and the mixture of sample and Fe-pellets rapidly cooled. Consequently, sufficient heating was only for a short time, in fact too short to entirely melt and oxidize

the samples. Indeed, inspection of the left-over material inside the crucible after several measurements demonstrated that the nickel (Ni) foil used to wrap the samples was only partially molten and even retained its original shape. Even though the meteorite samples were powdered and were closely wrapped into the Ni-foil together with the two Fe-pellets, we were never certain if the meteorite aliquots were fully molten and oxidized. To make things worse, re-extractions to demonstrate complete melting and extraction of ^{14}C were not possible because the already oxidized Fe-pellets could not be re-heated. Hence, after a few samples the crucible was filled with an uncontrollable mix of partially to fully combusted samples together with fully and partly oxidized Fe-pellets; clearly unacceptable for high-quality measurements. During measurements in July 2018, two Fe-pellets wrapped in Ni foil (NI_003 in Table 1) was added directly after the re-extraction of the JaH 073 aliquot (JaH073_006) to check whether such a re-extraction procedure would be more successful. Indeed, the number of extracted ^{14}C atoms was higher than the number of ^{14}C atoms released from the previously measured procedural blanks. However, this finding does not necessarily demonstrate that the remainder of the meteorite aliquot was fully oxidized, considering that some of the subsequently measured Fe-pellets, which are used as system blanks, were relatively high in released ^{14}C (e.g., BL_2FE_002). *Second*, though the pellets were of high purity Fe (99.99+), they nevertheless contained significant traces of carbon (not specified by the manufacturer), which was highly heterogeneous amongst the different pellets. This heterogeneity was tested for by measuring the amount of released CO_2 as a function of pellet mass, but no correlation was found. Note that an ill-defined and non-reproducible background contribution of CO_2 clearly prohibits high quality ^{14}C extractions.

This setup was very similar to the system described by Minami et al. (2001), which itself was modified after Jull et al. (1993). Briefly, in their method the authors mixed samples with about 2 g of high purity Fe and placed this mixture in an Al_2O_3-crucible. The crucible (and its lid) was pre-heated prior to their use. Samples were preheated at 500°C in a separate muffle furnace. Extraction of CO_2 gas from the pre-heated samples in the pre-heated Al_2O_3-crucible was via RF heating. However, this system also suffered from incomplete sample combustion and a considerable background blank. In addition, the system is designed to break the vacuum, and change and clean the crucible after every measured sample. This limitation is exactly what we want to avoid in our system.

Sample/blank ID	Sample mass (mg)	Measured CO_2[a] (10^{-2} cm^3)	C equivalence (µg)	Diluted CO_2[a,b] (10^{-2} cm^3)	C equivalence (µg)	$F^{14}C$[c]	$\delta^{13}C$ (‰)[f]	$(^{14}C/^{12}C)_{abs}$ (10^{-12})	N_{14} (10^4 atoms)	N_{14} (10^6 atoms/g)[g]	T_{14} (ka)
Pre-heating at 31.2 A (~500°C) for 1 hour											
May 2018											
BL_2FE_001		0.863±0.01	4.31	3.63±0.03	18.14	0.068±0.004	-9.9	0.081±0.005	7.34±0.4		
NI_001		1.43±0.01	7.15	1.88±0.02	9.38	0.392±0.014	-17.2	0.457±0.017	21.5±0.8		
JaH073_005	50.10	3.59±0.03	17.92	3.59±0.03	17.92	1.35±0.02	-19.4	1.57±0.02	120±2	26.1±0.5	18.7±0.5
JaH073_005_RE		0.483±0.003	2.41	3.01±0.02	15.04	0.125±0.005	-8.6	0.148±0.006	11.2±0.5		
July 2018											
BL_2FE_002		7.26±0.06	36.26	3.17±0.03	15.85	0.601±0.009	-18.2	0.699±0.010	55.6±0.94		
BL_2FE_003		3.17±0.03	15.85	3.17±0.03	15.85	0.284±0.005	-10.7	0.336±0.006	26.7±0.52		
NI_002		1.93±0.02	9.65	1.93±0.02	9.65	0.555±0.013	-8.1	0.659±0.015	31.9±0.77		
JaH073_006	50.14	3.29±0.03	16.45	3.29±0.03	16.45	1.53±0.01	-9.5	1.81±0.02	117±2	27.6±0.4	17.1±0.4
JaH073_006_RE		0.759±0.006	3.79	3.27±0.03	16.31	0.216±0.005	-7.5	0.257±0.006	21.1±0.52		
NI_003[d]		3.92±0.03	19.55	3.92±0.03	19.55	0.856±0.009	-8.1	0.175±0.004	67.8±0.91		
BL_021[e]		3.17±0.03	15.85	3.17±0.03	15.85	0.145±0.004	-1.4	2.66±0.02 0.699±0.010	13.9±0.39		
August 2018											
BL_2FE_005		5.18±0.04	25.84	3.45±0.03	17.23	0.416±0.002	-21.5	0.480±0.002	62.2±0.6		
BL_2FE_006		5.09±0.04	25.41	3.33±0.03	16.62	0.407±0.002	-23.6	0.468±0.003	59.6±0.6		
NI_005		2.86±0.02	14.30	2.86±0.02	14.30	0.488±0.012	-17.2	0.569±0.014	40.8±1.0		
JaH073_008	50.09	4.23±0.03	21.10	2.76±0.02	13.78	1.25±0.01	-17.9	1.46±0.01	113±2	44.8±0.5	14.7±0.3
JaH073_008_RE		5.73±0.05	28.60	3.78±0.03	18.86	0.521±0.003	-21.6	0.601±0.003	86.2±0.9		
No pre-heating											
August 2018											
BL_2FE_004		3.86±0.01	19.29	3.86±0.03	19.29	0.276±0.002	-18.7	0.321±0.002	31.0±0.3		
NI_004		5.35±0.03	26.70	3.50±0.03	17.49	0.402±0.002	-19.9	0.466±0.002	62.4±0.6		
JaH073_007	50.56	13.66±0.11	68.22	3.97±0.03	19.81	0.470±0.017	-28.1	0.535±0.020	121±2	39.8±0.4	13.8±0.3
JaH073_007_RE		8.88±0.07	44.36	3.83±0.03	19.12	0.656±0.002	-22.2	0.765±0.003	106±1		

BL_2FE – system blank, NI – procedural blank, RE – sample re-extraction. All uncertainties are 1 σ.

[a] CO_2 volumes are at 20°C.

[b] CO_2 volumes submitted to AMS – in order to reach the measurable C amount gas expanded into a known volume and a portion collected, or with added ^{14}C-free CO_2 carrier.

[c] Fraction modern carbon normalized to $\delta^{13}C$ of -25‰VPDB and AD 1950.

[d] Re-extraction measurement done by adding two Fe-pellets wrapped in Ni foil.

[e] CO_2 shot blank.

[f] The measured $\delta^{13}C$ of the sample, used to determine the $^{12}C/C_{TOTAL}$ for the sample.

[g] N_{14} per gram sample calculated using the sum of ^{14}C atoms from sample and re-extraction measurements.

Table 1. Results of the extraction of system blanks, procedural blanks, and samples from the Fe-pellet experiments.

2. *Stainless Steel (AISI 304) as a Combustion Catalyst*

As demonstrated in the previous section, Fe-pellets were not suitable for our combustion and extraction setup for various reasons. *First*, the carbon content was high and variable, and *second*, they oxidized and therefore cooled too quickly to enable complete and throughout melting and oxidation of the samples. Thus, we decided to change the combustion catalyst to stainless-steel pellets with a certified carbon concentration (AISI 304, Fe/Cr18/Ni10, carbon concentration of 220 ppm). The known and homogeneous carbon content in the steel pellets would make it possible to prove whether all carbon from the steel pellet, and with it likely all carbon from the sample, was oxidized and released as CO_2, enabling an internal quality control. In addition, stainless steel is known to be relatively resistant against oxidation. We therefore expected that stainless-steel pellets would stay at high temperatures for longer time than Fe-pellets, allowing for a more complete melting and oxidation of the samples. Note, however, that the higher resistance of stainless steel to oxidation was proven for atmospheric pressure and at room temperature but not for a partial pressure of 30 mbar UHP O_2 and at 1600°C. For preparing the catalysts, we used a stainless-steel rod (6 mm diameter and 250 mm length) from Advent Research Materials Ltd. The rod was cut into thin disks using a diamond rock saw. The individual disks were then polished using a rock polisher to remove rough edges. The produced pieces varied in mass from 155 mg to 477 mg. In total we produced seven pieces.

Initial tests with the stainless-steel disks were promising; the stainless steel did not oxidize before reaching its melting temperature of ~1450°C. Equally important, the disks stayed at the maximum temperature for the entire extraction. The first analysis of a 155 mg stainless-steel disk released 37.1 µg of carbon; the second and third re-extractions released additionally 8.6 µg of carbon. From the released carbon and the mass of the studied pellet, we calculate a carbon concentration of 295 ppm, which was higher than the specified value pf 220 ppm. A second steel disk of 477 mg, however, only released ~180 ppm carbon, indicating that either the steel was not as homogeneous as expected with respect to carbon and/or that the extraction procedure was not as reproducible as anticipated. Turning the argument around, the extraction of 155 mg steel pellet together with our homogeneous sample powder resulted in 4.31 mbar of CO_2 in the capillary. Therefore, extracting the CO_2 from a 477 mg steel disk should result in 13.3 mbar of CO_2 from the steel alone, not to mention the CO_2 released from the sample. In contrast, we extracted only 5.46 mbar of CO_2, i.e., far too little.

In addition to the problem of fully releasing the $CO_2$from the steel and the sample, AMS measurements demonstrated an increase of the ^{14}C blank after each sample, even though re-extractions were performed for all samples (Table 2). Again, the data indicated that complete melting and carbon release could not be achieved. Eventually the system behaved very similar to the set-up using Fe-pellets, hence we concluded that using stainless steel as a combustion catalyst is not feasible in our extraction system. We therefore changed the system to its current final set-up (see below). Note that the previously mentioned system in Japan (Minami et al. 2006) has also undergone many changes over the years. For example, in their system instead of adding pure Fe to the samples, steel with a known carbon concentration of 0.0519±0.0012 wt% is added. The reason for choosing this steel is its carbon content, i.e., combustion of 3 g of the steel delivered ~1 mg of carbon, an amount necessary for the AMS measurements. In their current system, the Al_2O_3-crucible is pre-heated at 1000°C and the samples are pre-heated in a muffle furnace at 500°C in air before combustion using RF heating (Minami et al. 2006). Though the system gives reliable results, it is still necessary to break the vacuum, and clean and change the crucible after every sample, significantly reducing sample throughput.

Sample/blank ID	Sample mass (mg)	Measured CO_2[a] (10^{-2} cm^3)	C equivalence (μg)	Diluted CO_2[a,b] (10^{-2} cm^3)	C equivalence (μg)	$F^{14}C$[x]	$\delta^{13}C$ (‰)[d]	$(^{14}C/^{12}C)_{abs}$ (10^{-12})	N_{14} (10^4 atoms)	N_{14} (10^6 atoms/g)[e]	T_{14} (ka)
Pre-heating at 31.2 A (~500°C) for 1 hour											
November 2018											
BL_SS_001		7.44±0.06	37.12	3.19±0.03	15.94	0.325±0.006	-31.31	0.367±0.007	68.4±1.5		
BL_SS_001_RE(1)		1.35±0.01	6.72	1.82±0.01	9.07	0.258±0.008	-6.90	0.308±0.009	14.0±0.4		
BL_SS_001_RE(2)		0.380±0.003	1.89	2.89±0.02	14.41	0.081±0.003	-0.91	0.097±0.004	7.02±0.3		
NI_006		9.82±0.08	49.01	2.86±0.02	14.30	0.256±0.006	-31.29	0.290±0.006	71.2±1.7		
JaH073_009	50.14	9.78±0.08	48.84	2.78±0.02	13.87	0.765±0.010	-25.70	0.876±0.012	143±2	35.8±0.4	15.6±0.4
JaH073_009_RE		5.40±0.04	26.96	3.55±0.03	17.74	0.231±0.005	-16.29	0.269±0.006	36.4±0.9		
BL_SS_002		9.42±0.08	47.03	2.64±0.02	13.18	0.210±0.006	-34.08	0.237±0.007	55.8±1.6		
NI_007		17.23±0.01	86.05	3.19±0.03	15.94	0.191±0.004	-26.73	0.218±0.005	94.1±2.3		

BL_SS – system blank, NI – procedural blank, RE – sample re-extraction. All uncertainties are 1 σ.
[a]CO_2 volumes are at 20°C.
[b]CO_2 volumes submitted to AMS – in order to reach the measurable C amount gas expanded into a known volume and a portion collected, or with added ^{14}C-free CO_2 carrier.
[c]Fraction modern carbon normalized to $\delta^{13}C$ of -25‰VPDB and AD 1950.
[d]The measured $\delta^{13}C$ of the sample, used to determine the $^{12}C/C_{TOTAL}$ for the sample.
[e]N_{14} per gram sample calculated using the sum of ^{14}C atoms from sample and re-extraction measurements.

Table 2. Results of the extraction of system blanks, procedural blanks, and samples from the stainless-steel experiments.

c. Current Analytical Setup: High Frequency Generator and Pt-Crucible

From the various set-ups presented before, the RF heating approach proved to be a good solution for one of the major problems for all heating experiments – unnecessary heating of a large portion of crucible material to finally heat a small sample. Heating a large and heavy crucible usually increases the blank due to, *first*, longer heating cycles and, *second*, more heated material. This was the argument for the combustion catalyst, which, however, remained to be the problematic part; either it produced a too high CO_2 background and/or it oxidized too quickly to guarantee a throughout melting and oxidation of the samples. For RF heating and combustion, the material used either as a crucible or as a combustion catalyst must be conductive, inert against oxidation, and should not change its properties even when heated several times. Platinum (Pt) became the material of our choice and hence, a Pt-crucible was ordered from Labor-Platina Ltd with the following dimensions: 14 mm outer diameter, 1 mm wall thickness, 80 mm length, and 3 mm bottom thickness.

The Pt-crucible was placed inside an outer Qtz-glass crucible (Figure 1), analogous to the double-walled Qtz-crucible system used before. Again, the bottom 2-3 cm of the Qtz-crucible was filled with Qtz-granulate on which the Pt-crucible was placed to avoid direct contact between the hot Pt crucible and the outer Qtz crucible. For safety reasons, a rhenium wire placed between the upper part of the Pt-crucible and the outer Qtz-crucible prevented the Pt-crucible to touch the outer glass because, again, direct contact could locally heat and break the glass, and thus the vacuum. Multiple heating tests were performed before first meteorite aliquots were measured. *First*, tests were performed to see if the crucible can reach the temperature needed for extraction, i.e., what is the maximum temperature that can be reached without melting or damaging the platinum, <1768°C. With our set-up is it not straightforward to directly measure the temperature; however, the glow-color indicates that the temperature is indeed approaching the melting temperature of Pt. The temperatures of the Qtz- and Pt-crucibles were measured during pre-heating and extraction using an infrared (IR) thermometer camera (see below). *Second*, we performed the same tests but with an O_2 flow of 30 ml/min to check if and how the gas flow cools the crucible. It was indeed observable that the O_2 flow resulted in a cooling of the Pt-crucible, but it was easy to still reach the required temperature by simply adjusting the power of the RF generator. Still, the required temperature can be reached at just one third of the maximum power available with this type of RF generator. *Third*, first samples were measured to determine the pre-heating settings for this system. The tests gave pre-extraction currents of 90.2 A (~500°C) and extraction currents of 210 A (~1600°C) (also see below). Note that the new home-made RF coil recently installed is even more efficient than the original commercial one. The major advantage of this new coil set-up is that introducing an O_2 flow or an O_2 partial pressure no longer results in a cooling of the crucible. Therefore, with or without O_2 flow the extraction current is always close to 120 A, which is only about 20% of the maximum that can be reached with this type of RF generator.

Up to now, 17 sets of samples (system blank, procedural blank, sample, sample re-extraction) were performed. In addition, seven smaller sets of measurements were performed to determine the pre-heating current for the new coil (see above). Therefore, in total, 23 pieces of Al foil and 17 meteorite aliquots are already inside the Pt-crucible at the time of writing (September 2019). The extraction system remained fully functional for 17 meteorite aliquots without cleaning and without breaking the vacuum. For the last three meteorite samples, however, the AMS measurements revealed a successively lower yield of ^{14}C atoms. This finding, in addition with the finding, that procedural blanks did not produce any CO_2 gas, indicates that the Pt-crucible was too full and heating was no longer effective. Consequently, both crucibles were emptied and cleaned.

All initial heating tests were performed by continuously inspecting the interior of the crucible, which is visible through the glass opening at the top of the sample holder, located directly above the crucible. After a few measured samples, some of the Al from the molten foils unfortunately condensed onto the glass window and prohibits a direct view into the crucible. Although this is an inconvenience, it is not a limitation for the performance of the system. For the initial tests, the temperature was regularly checked using an IR thermometer. In the following, '*top*' refers to the part of the Qtz-crucible that is visible directly above the RF coil, and '*bottom*' refers to the part of the Qtz-crucible that is visible directly below the coil, i.e., the part filled with Qtz-granulate. During pre-heating, the top of the Qtz-crucible is at a temperature of ~180°C and the bottom is at ~90°C. During extraction, the top of the Qtz-crucible is at max. 550°C and the bottom is at max. 250°C. Immediately after the RF heating has been switched off, the top of the Qtz-crucible is at ~350-400°C and the bottom is at ~200°C. The temperature reading therefore clearly indicates an efficient cooling of the Qtz-crucible. Remember that the outside of the outer Qtz crucible is in contact to air and therefore convection is a very efficient way of cooling. For the temperature measurements of the Qtz-crucible we used an emissivity (ε) of 0.90, which is valid for glass. The IR camera was also used to measure the temperatures of the Pt-crucible during pre-heating and extraction. Temperature measurements of the Pt-crucible were done by setting the emissivity ε to 0.16 (Platinum typically ~0.14-0.18). Based on ten temperature measurements, the bottom of the Pt-crucible, i.e., the thickest part of the crucible, reaches 498±6°C during pre-heating. During extraction, the temperature reading showed 2024±68°C , which is unreasonable because it is far above the melting point of Pt. Note that despite this temperature reading no damage to the Pt-crucible or to the Qtz-crucible could be observed. After each measurement, the inside of the crucible is inspected from above, through the opening in the sample holder. So far we observe efficient melting of all samples.

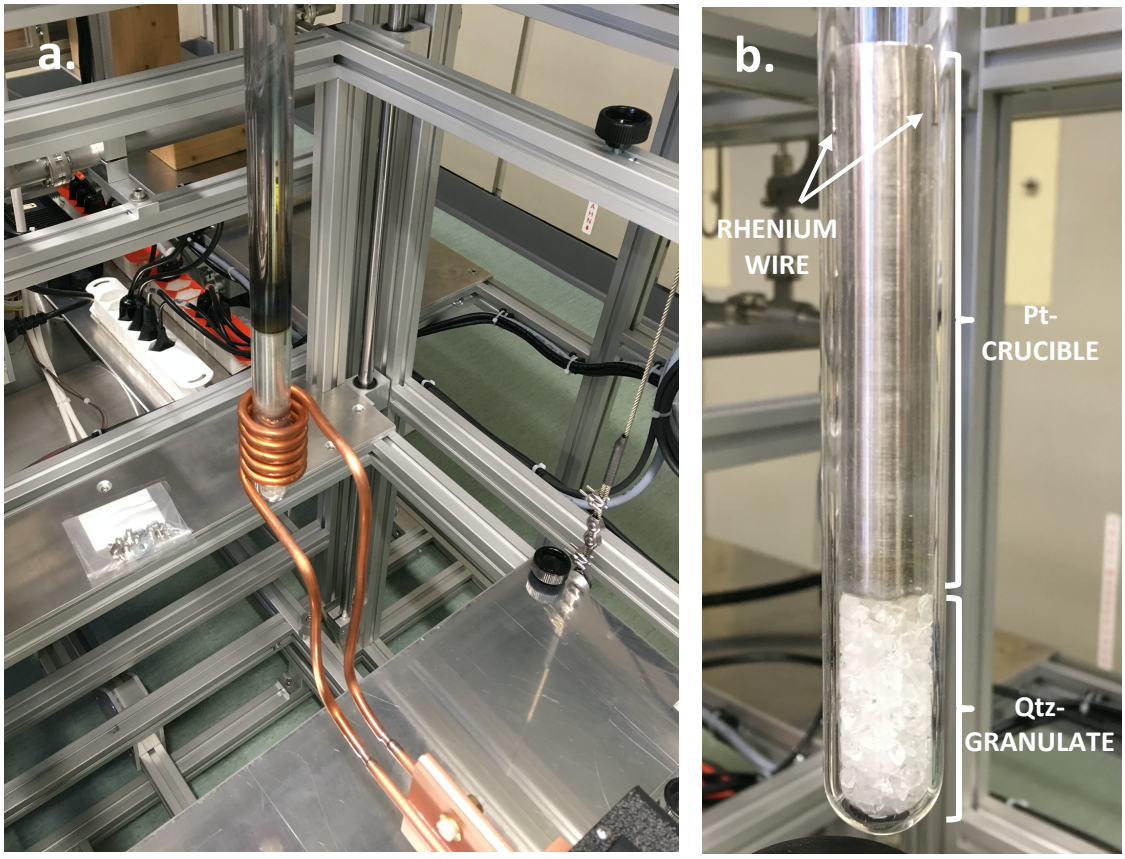

Figure 1. a. The current analytical setup of the combustion-extraction system. The RF coil is placed around the Qtz-crucible, hosting the Pt-crucible inside; b. A close-up of the crucible setup. The Pt-crucible rests on a layer of Qtz-granulate. On the top of the Pt-crucible two pieces of rhenium wire are visible, separating the Pt- and the Qtz-crucible.

3. CURRENT ANALYTICAL PROCEDURE

The current extraction protocol contains minor changes in the heating protocol, relative to the one described earlier by Mészáros et al. (2018), however the sample preparation is still conducted according to the procedure previously stated. In summary, after sample milling, the sample fraction with a grain-size of 125-250 μm is treated first for 30 mins with 6.0 N HCl to dissolve carbonates, and then with ethanolamine-thioglycollate (EATG) for 2 days to remove iron oxides and hydroxides. As shown by Mészáros et al. (2018) this leaching procedure removes unwanted compounds without affecting the primary minerals (see Introduction), which contain the *in situ* produced ^{14}C.

In the current set-up, sample pre-heating is at a RF current of 60.5 A, which corresponds to ~500°C. Currently, the pre-heating step lasts for one hour and takes place in a continuous UHP O_2 flow with continuous pumping. This step removes adsorbed water and terrestrial contaminants. Next, the crucible is disconnected from the pump, an O_2 partial pressure of 30(±5) mbar is established, and the generator current is gradually increased in 10 A steps (50°C min^{-1}). After each increase of the current, the glow-color of the crucible and the decrease in the O_2 partial pressure inside the crucible are noted. A drop in O_2 pressure during extraction is expected because the aim of the extraction protocol is to oxidize the sample.

The evolved gases are expanded into a high-temperature gas purification furnace (Carbolite-Gero®), working in the temperature range between 500°C and 1000°C. The furnace contains quartz spherules, silver wool, and copper-oxide, supporting purification and/or oxidation of the gas. The expanded gas is collected in a helix that is cooled with liquid nitrogen (LN_2). The total extraction lasts for 10 mins at a current of 121.0 A (~1600°C). After extraction, the current of the RF generator is reduced to 60.5 A (~500°C), the crucible cools down, and any remaining O_2 can be pumped away safely. After the system is back to its minimum background pressure below 5×10^{-4} mbar, the gas purification and CO_2 collection steps are carried out as described by Mészáros et al. (2018). In brief, the gases collected in the helix are expanded into a known volume and the pressure is noted. Next, the water trap is cooled to a temperature of -78°C to remove remaining water. Next, the remaining gas is transferred to a cold finger cooled with LN_2. Any remaining unfrozen gas is pumped away, the LN_2 is removed, and a cold trap set to a temperature of -100°C is applied to the cold finger. The released CO_2 gas is trapped in a glass capillary that is cooled with LN_2. The collected CO_2 gas is expanded into a known volume above and including the capillary and the pressure is noted. If the amount of collected carbon is too low (<10 μg C) for a reliable $^{14}C/^{12}C$ measurement using the MICADAS system at the Department of Chemistry and Biochemistry, University of Bern, we add extra ^{14}C-free CO_2 (see also Mészáros et al. 2018).

4. AMS MEASUREMENTS AND DATA REDUCTION

The ^{14}C analyses to determine the $^{14}C/^{12}C$ ratios were conducted using the MICADAS at the Laboratory for the Analysis of Radiocarbon with AMS (LARA) at the Department of Chemistry and Biochemistry, University of Bern (Szidat et al. 2014), as described in Mészáros et al. (2018). In summary, glass ampules containing the collected CO_2 gas were introduced into the gas interface of the MICADAS, cracked open, the CO_2 gas was mixed with helium gas, and this mixture was transferred to the gas ion source. The ^{14}C results are expressed as $F^{14}C$ (fraction modern carbon) values. For calculating the ^{14}C terrestrial ages we are using the ^{14}C data reduction equations given by Hippe et al. (2013) and Hippe and Lifton (2014). To start, the absolute $^{14}C/^{12}C$ ratio is determined using the measured $F^{14}C$ value and this ratio is used to calculate the number of ^{14}C atoms (N_{14}). The number of ^{14}C atoms per gram of sample is then used to calculate the specific activity (dpm/kg) of the sample. Finally, the terrestrial age is

calculated using the specific activity of the samples and the saturation activity for the studied meteorite type. For a detailed description of the data reduction calculations the reader is referred to Mészáros et al. (2018). For most of the terrestrial ages, though, we now use the ^{10}Be-^{14}C dating technique, which is more reliable than using ^{14}C alone.

5. CURRENT PERFORMANCE: RESULTS AND DISCUSSION

a. System and Procedural Blanks

As already described by Mészáros et al. (2018), we distinguish two types of blanks: system blanks and procedural blanks. The abbreviation used in Tables 3 and 4 for system blanks is BL and for procedural blanks it is AL. For the current extraction system, as it has been for the setup used by Mészáros et al. (2018), system blanks are performed by introducing a known amount of ^{14}C-free CO_2 gas into the system and applying the normal gas separation and gas cleaning steps (see above). For procedural blanks we measure an Al-foil, used to wrap the samples, in the same way we usually measure the samples. Table 3 summarises the results of the measurements of the various aliquots of the JaH 073 strewn field together with the associated system and procedural blanks at three different pre-heating currents. One can see that both system and procedural blanks become lower with higher pre-heating current. From the data we concluded that a pre-heating current of ~90 A is highly efficient for the removal of terrestrial contamination but is still low enough to not release the cosmogenic ^{14}C from the sample. The extracted number of ^{14}C atoms (N_{14}) for our system and procedural blanks is comparable to that reported by Mészáros et al. (2018), where the N_{14} values for blanks were well-established for pre-heating at 500°C using the convection oven system, where temperature could be directly monitored. We also spotted that successive heating cycles helped cleaning the crucible and with every heating cycle, i.e., blank and sample measurement, both system and procedural blanks became lower. Importantly, for the established pre-heating procedure (1 hour at 90.2 A) the system and procedural blanks are almost indistinguishable, i.e., they range between 3.18×10^4 ^{14}C atoms to 4.92×10^4 ^{14}C atoms, which is a minor correction for the number of ^{14}C atoms usually released from the sample, which is in the range of 100×10^4 or more. If we compare our system blanks to the system blanks by Mészáros et al. (2018) obtained using an earlier set-up we find that our blanks for Coil 1 and a pre-heating current of 90.2 A are relatively constant in the range of 4.28×10^4 and 4.92×10^4 ^{14}C atoms, with an average of $4.6(\pm0.3)\times10^4$ ^{14}C atoms. In comparison, the earlier set up gave system blanks ranging from 1.35×10^4 to 5.06×10^4 ^{14}C atoms, with an average of 2.6×10^4 ^{14}C atoms (Mészáros et al. 2018). The system blanks obtained using Coil 2 are in the range 4.36×10^4 and 6.79×10^4 ^{14}C atoms with an average of $5.6(\pm1.2)\times10^4$ ^{14}C atoms. The upper limit is slightly higher compared to the one obtained by using Coil 1. This slight increase is most likely due to the fact that we had to replace the outer Qtz-crucible because it cracked after 37 measurements/heating cycles. We cannot exclude that the new Qtz-crucible might have released some ^{14}C during the first few times of usage. In addition, in the set-up using Coil 1 and the old outer Qtz-crucible, a rhenium wire was used to separate the top of the inner Pt-crucible from the outer Qtz-crucible. After changing to Coil 2 and replacing the outer Qtz-crucible, we changed to a tungsten wire for the separation. Apparently, the tungsten wire releases slightly more ^{14}C atoms than the rhenium wire. This finding is also supported by the visual inspection; the tungsten wire clearly oxidised, its colour changed gradually with each heating cycle to pale yellow. With the next crucible cleaning, the tungsten wire will be discarded and replaced a by rhenium wire.

As already discussed by Mészáros et al. (2018), due to high procedural blanks produced from the non-pre-heated Al-foil, all measurements have to be performed with a pre-heating step; we no longer conduct measurements without pre-heating. The procedural blanks used to correct the samples are listed in Tables 3 and 4. As already mentioned, these blanks fall gradually with increasing pre-heating current.

Procedural blanks using Coil 2 were slightly higher than for Coil 1. Unfortunately, no procedural blank is available for measurements with a pre-heating current of 50.6 A, because the sample was lost during AMS measurements.

The blank of 2.6×10^4 ^{14}C atoms obtained using Coil 1 is about a factor of 8-9 lower than the extraction blanks published by Lifton et al. (2001, 2015) but is comparable to the blank level reached at the new extraction system established at ETH Zürich of $1.92(\pm0.56)\times10^4$ (Lupker et al. 2019). Assuming now that we can safely detect ^{14}C concentrations more than three times higher than the blank, i.e., we can safely detect 8×10^4 ^{14}C atoms/g and assuming further that we measured samples masses in the range 50 mg we calculate that we can relatively safely measure terrestrial ages up to 45 ka.

b. Reproducibility: JaH 073 Strewn Field Data

The reproducibility of sample measurements is satisfying, though from the first data it seems that the reproducibility was slightly better for the set-up using Coil 1 (after pre-heating with 90.2 A) than for the set-up using Coil 2 (after pre-heating with 60.5 A). Note that the second JaH 073 aliquot (MS_JaH073_017) measured using Coil 2 was measured after replacing the outer Qtz-crucible, hence the higher number of extracted ^{14}C atoms rather indicates contamination adhering to the inside of the Qtz-crucible than problems with the reproducibility (Table 4). The JaH 073 strewn field sample consists of a homogenized sample powder, therefore sample heterogeneity is not expected. The found deviations therefore likely indicate the reproducibility of the total sample extraction and cleaning procedure. From the four measurements we calculate a grand average specific ^{14}C concentration of 25.3×10^6 atoms/g with a 1σ standard deviation of 2.0×10^6 atoms/g, i.e., 7.8%. For future studies we consider the standard deviation of 2.0×10^6 atoms ^{14}C/g as the external systematic reproducibility of our extraction procedure for meteorite samples with a ^{14}C terrestrial age measured in the range of 0 to 20 ka, i.e., for specific ^{14}C concentrations in the range $(20\text{-}30)\times10^6$ atoms/g.

Sample/blank ID	Sample mass (mg)	Measured CO_2[a] (10^{-2} cm^3)	C equivalence (µg)	Diluted CO_2[a,b] (10^{-2} cm^3)	C equivalence (µg)	$F^{14}C$[c]	$\delta^{13}C$ (‰)[e]	$(^{14}C/^{12}C)_{abs}$ (10^{-12})	N_{14} (10^4 atoms)	N_{14} (10^6 atoms/g)[f]	T_{14} (ka)
				November to December 2018							
				Coil 1, pre-heating at 50.6 A for 1 hour							
BL_022		4.31±0.04	21.50	3.30±0.03	16.50	0.156±0.005	-6.69	0.186±0.006	15.4±0.5		
AL_007		1.29±0.01	6.46	1.29±0.01	6.26			Sample lost during AMS measurement			
JaH073_010[d]	50.29	8.87±0.07	44.27	3.81±0.03	19.04	0.695±0.008	-23.81	0.799±0.010	76.3±2.6	36.9±0.5	15.4±0.4
JaH073_010_RE		0.380±0.003	1.89	2.29±0.02	14.62	0.095±0.006	-2.82	0.114±0.007	8.37±0.52		
				Coil 1, pre-heating at 70.4 A for 1 hour							
BL_023		2.66±0.02	13.26	2.66±0.02	13.26	0.105±0.005	-11.03	0.124±0.006	8.24±0.43		
AL_008		1.36±0.01	6.80	1.36±0.01	6.80	0.610±0.018	-39.07	0.679±0.020	23.2±0.70		
JaH073_011	50.01	3.38±0.03	16.88	3.38±0.03	16.88	1.56±0.02	-32.26	1.76±0.18	126±2	27.0±0.4	17.9±0.5
JaH073_011_RE		0.173±0.001	0.86	2.77±0.02	13.84	0.114±0.006	-13.10	0.134±0.007	9.29±0.50		
				Coil 1, pre-heating at 90.2 A (~500°C) for 1 hour							
BL_024		2.69±0.02	13.44	2.69±0.02	13.44	0.062±0.005	-9.82	0.073±0.006	4.92±0.39		
AL_009		0.086±0.001	0.43	2.70±0.02	13.50	0.045±0.005	-8.89	0.054±0.005	3.63±0.37		
JaH073_012	50.01	0.62±0.01	3.10	3.26±0.03	16.25	1.20±0.02	-12.73	1.42±0.02	112±2	23.9±0.4	18.9±0.5
JaH073_012_RE		0.121±0.001	0.60	2.71±0.02	13.51	0.096±0.005	-10.08	0.113±0.006	7.65±0.43		
BL_025		2.74±0.02	13.70	2.74±0.02	13.70	0.054±0.005	-8.42	0.064±0.005	4.38±0.38		
AL_010		0.086±0.001	0.43	2.75±0.02	13.72	0.039±0.004	-9.37	0.046±0.005	3.18±0.36		
JaH073_013	50.16	0.76±0.01	3.79	3.42±0.03	17.08	1.03±0.01	-12.35	1.21±0.02	100±2	22.4±0.3	19.5±0.5
JaH073_013_RE		0.104±0.001	0.52	2.73±0.02	13.61	0.149±0.007	-10.52	0.176±0.008	12.0±0.5		

BL – system blank, AL – procedural blank, RE – sample re-extraction. All uncertainties are 1 σ.
[a]CO_2 volumes are at 20°C.
[b]CO_2 volumes submitted to AMS – in order to reach the measurable C amount gas expanded into a known volume and a portion collected, or with added ^{14}C-free CO_2 carrier.
[c]Fraction modern carbon normalized to $\delta^{13}C$ of -25‰VPDB and AD 1950.
[d]Not corrected with blank.
[e]The measured $\delta^{13}C$ of the sample, used to determine the $^{12}C/C_{TOTAL}$ for the sample.
[f]N_{14} per gram sample calculated using the sum of ^{14}C atoms from sample and re-extraction measurements.

Table 3. Results of the extraction of system blanks, procedural blanks, and samples from tests using Coil 1.

Sample/blank ID	Sample mass (mg)	Measured CO_2[a] (10^{-2} cm^3)	C equivalence (µg)	Diluted CO_2[a,b] (10^{-2} cm^3)	C equivalence (µg)	$F^{14}C$[c]	$\delta^{13}C$ (‰)[d]	$(^{14}C/^{12}C)_{abs}$ (10^{-12})	N_{14} (10^4 atoms)	N_{14} (10^6 atoms/g)[e]	T_{14} (ka)
Coil 2, preheating at 60.5 A (~500°C) for 1 hour											
January to February 2019											
BL_032		3.12±0.03	15.60	3.12±0.03	15.60	0.073±0.004	-5.24	0.087±0.005	6.79±0.36		
AL_017		0.155±0.001	0.78	2.82±0.02	14.10	0.074±0.004	-6.16	0.089±0.005	6.26±0.37		
JaH073_016	50.14	1.29±0.01	6.46	1.72±0.01	8.60	2.36±0.03	-16.87	2.75±0.03	112±2	23.9±0.4	18.9±0.5
JaH073_016_RE		0.173±0.001	0.86	2.76±0.02	13.80	0.088±0.004	-3.27	0.105±0.005	7.30±0.34		
BL_036		2.88±0.02	14.38	2.88±0.02	14.38	0.051±0.004	-8.08	0.060±0.004	4.36±0.32		
AL_0019		0.449±0.004	2.24	3.02±0.01	15.10	0.056±0.004	-8.11	0.066±0.004	5.02±0.33		
JaH073_017	50.05	2.52±0.02	12.58	2.52±0.02	12.58	2.06±0.02	-30.00	2.34±0.002	142±2	31.2±0.4	16.7±0.4
JaH073_017_RE		1.22±0.01	6.12	1.66±0.01	8.30	0.283±0.010	-24.47	0.324±0.01	13.5±0.5		

BL – system blank, AL – procedural blank, RE – sample re-extraction. All errors are 1 σ.

[a]CO_2 volumes are at 20°C.

[b]CO_2 volumes submitted to AMS – in order to reach the measurable C amount gas expanded into a known volume and a portion collected, or with added ^{14}C-free CO_2 carrier.

[c]Fraction modern carbon normalized to $\delta^{13}C$ of -25‰VPDB and AD 1950.

[d]The measured $\delta^{13}C$ of the sample, used to determine the $^{12}C/C_{TOTAL}$ for the sample.

[e]N_{14} per gram sample calculated using the sum of ^{14}C atoms from sample and re-extraction measurements.

Table 4. Results of the extraction of system blanks, procedural blanks, and samples from tests using Coil 2

6. CONCLUSIONS

The ^{14}C extraction line at the University of Bern has undergone three major improvements concerning the extraction and combustion system since its first description by Mészáros et al. (2018). In its final form, the extraction and combustion system comprises of an outer wall Qtz-glass-crucible with an inner Pt-crucible, heated by radio-frequency. The blanks are reasonably constant and low in the range 2.6×10^4 ^{14}C atoms, which is comparable to other sophisticated systems (e.g., Lupker et al. 2019) and lower than some of the other systems (e.g., Lifton 2001, 2015). The system shows the tendency of decreasing blanks with increasing number of heating cycles, which indicates that in future routine applications the blank levels can even be lower. The current blank levels enable determining terrestrial ages up to about 45 ka. Using our reference sample from the JaH 073 strewn field, we *first* determined the adequate pre-heating and extraction RF currents, and *second*, we tested the system for reproducibility. The latter is in the range 7-8% for ^{14}C concentrations in the range $(20\text{-}30)\times10^6$ atoms, i.e., for meteorites with terrestrial ages in the range 0-20 ka. Finally, with the current system we have reached our goal to measure a large number of meteorites for ^{14}C samples without breaking the vacuum. Currently, measurements of other previously measured strewn fields, such as Jiddat al Harasis 091, as well as strewn fields not yet measured for ^{14}C are in progress.

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